Plasmonics: A promising path for future interconnects

Oak Ridge National Laboratory

oore's Law—that the number of transistors on integrated circuits doubles approximately every two years [1] shows no sign of abating anytime soon. Semiconductor fabrication capabilities, currently based on a 22-nanometer (nm) process, will eventually reach the limits imposed by quantum mechanics, but parallelization will allow computational power to keep increasing at an exponential rate well into the future. However, a stark disconnect has emerged between theoretical and actual computing performance. This disconnect is due to a communications speed limit between processing cores, memory cache, and storage, and it is the primary performance bottleneck that prevents harnessing available computational power.

The interconnects at the heart of today's microprocessors consist of copper wires measuring several tens of nanometers to a few millimeters in dimension depending on their function. One successful strategy that has provided performance gains over the past 40 years has been to increase the clock speed of the microprocessor. Clock speeds have increased by three orders of magnitude in 40 years but have begun to level off, at around 4–5 gigahertz, within the past five years. This is due to the success of another strategy which involves reducing the size of the transistors themselves. As more transistors are crammed onto a chip, the dimensions of the transistors and the copper wires that supply power, clock, and instruction signaling must also be reduced.

Unfortunately, as copper wires shrink in size and the signaling frequency increases, the wires exhibit both more electrical resistance and signal propagation delay. Chip designers have countered with lower signaling voltages and ingenious signaling network layouts, but the communications bottleneck will endure as long as copper wires remain the interconnect of choice.

By 2017 the electrical current required for chip power and signaling will likely exceed the material limits of copper metal according to the International Technology Roadmap for Semiconductors (ITRS) 2011 report [2]. Although numerous efforts to identify potential copper material replacements are under way, retaining the same interconnect strategy is likely to gain only an order of magnitude increase in performance, representing a literal kicking the can down the road. Technologies have been proposed to replace electrical signaling over copper, a full account of which can be found in the ITRS reports. Photonics is one of these proposed replacements because photons can

be generated easily, detected efficiently, and can have bandwidths three orders of magnitude greater than achievable with electrical signaling.

Silicon photonics is often heralded as the next generation of interconnect technology, capable of relatively low-loss, high-bandwidth optical signaling using integrated waveguides with cross sections as small as 200 nm x 200 nm. This size, while relatively small, is still an order of magnitude larger than today's current semiconductor fabrication process. If photonics, or any other potential technology, is to be a realistic contender to replace copper interconnects, it must have comparable dimensions to the transistor. Photonics is constrained by the diffraction limit: No dielectric element, resonator, or waveguide can have dimension less than half of the wavelength and still faithfully confine photons and function properly. Can we harness the advantages of optics at the nano-scale?

Yes—with plasmonics, a multidisciplinary field combining optics and solid-state physics, the study of optical fields bound to metal surfaces. A plasmon is a quantum mechanical quasiparticle consisting of collective oscillations of a metal's conduction electrons. A surface plasmon polariton (SPP) is a surface-bound propagating plasmon mode. One of the most intriguing aspects of plasmonics is for devices that operate well below the optical diffraction limit. This is due to some of the electromagnetic field energy being coupled to the metal's electron kinetic energy instead of being stored in the magnetic field.

As a result, plasmonic devices can effectively "squeeze" light into metal structures tens of nanometers in size, exceeding the optical diffraction limit by factors of 10 or more, yet retaining the large optical bandwidth. This is what makes plasmonics a promising contender to replace the copper interconnects in current architectures. Future plasmonic interconnects will require 1) sources of plasmons, 2) low-loss and high-confinement waveguides, and 3) plasmon detectors. In this article, we will provide a brief introduction and review of these three important technologies that will provide the necessary foundation for future plasmonic interconnects.

Plasmon sources

SPP sources are divided into two main technologies: nanolasers, which generate photons that are then coupled to plasmons, and SPASER-type devices, which are true nanoscale sources of plasmons. (SPASER stands for surface plasmon amplification of stimulated emission of radiation.) The cavity size of traditional lasers has a fundamental minimum, typically on the order of a few microns, imposed by the optical diffraction limit and round-trip cavity losses. As such, even state-of-the-art lasers are unsuitable for integration into chip architectures due to their size—they are simply too large.

Nanolasers exhibit all of the desirable properties of their larger cousins but with one major difference: The addition of metal within the cavity allows the cavity to be much smaller (see figure 1). By tuning the laser emission close to an SPP resonance, the nanolaser experiences both a large increase in the effective modal gain and group refractive index. This allows stimulated emission within a much smaller cavity. Nanolasers have recently been demonstrated with a mode volume of 0.4 cubic wavelengths (λ^3) and operating under electrical injection at room temperature in the important telecom band [3]. Over the next two years, we are likely to see even more impressive demonstrations of nanolasing with devices having smaller mode volumes, a selection of wavelengths, and tunable cavity configurations. Within five years, we will likely witness demonstrations of pulsed nanolasers with subfemtosecond pulse widths and the beginnings of integration with advanced silicon photonic devices.

Nanolasers, with their subdiffraction-limit mode volumes, are not ideal SPP sources for two specific reasons: at least one dimension has to be greater than $\lambda/2$, and nanolasers emit photons instead of plasmons and thus will experience some photon-plasmon coupling loss. SPASERs, the surface plasmon analog to lasers, may very well be the ideal localized plasmon source capable of ultrafast atto-second operation [4, 5] but are a much less mature technology in comparison to nanolasers. The most widely studied SPASER devices are comprised of

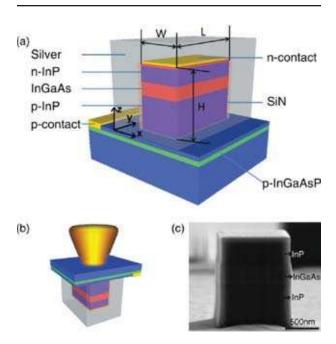


FIGURE 1. Nanolasers exhibit all of the desirable properties of their larger cousins but with one major difference: The addition of metal within the cavity allows the cavity to be much smaller. This schematic of a nanolaser (a) with light emission from the reverse side (b) consists of a semiconductor pillar (c) encapsulated with silver to form a metallic cavity. The semiconductor materials are as follows: indium gallium arsenide (InGaAs), silicon nitride (SiN), indium phosphide (InP), indium gallium arsenide phosphide (InGaAsP). Where the prefixes 'p-' and 'n-' denote positive and negative donor doping respectively, the metals are as follows: gold, platinum, and titanium. Reprinted figure with permission from Ding K, Liu ZC, Yin LJ, Hill MT, Marell MJH, van Veldhoven PJ, Nöetzel R, Ning CZ, Physical Review B, 85, 041301(R), fig.1, 2012. Copyright 2012 by the American Physical Society. Available at http://dx.doi.org/10.1103/PhysRevB.85.041301 [3]. Readers may view, browse, and/or download material for temporary copying purposes only, provided these uses are for noncommercial personal purposes. Except as provided by law, this material may not be further reproduced, distributed, transmitted, modified, adapted, performed, displayed, published, or sold in whole or part, without prior written permission from the American Physical Society.

metal nanoparticles, often 20–40 nm in diameter but as small as 1 nm, that are coated with a gain material (see figure 2). When excited, the gain medium supplies the energy for plasmon emission, with the nanoparticle itself acting as the resonant cavity. This results in the stimulated emission of coherent plasmons from the nanoparticle, albeit with a poorly defined emission profile. Placing a plasmonic waveguide close to a SPASER causes the

plasmons generated in the SPASER to couple to the waveguide.

However, SPASERs have only been demonstrated using optical excitation with external pump lasers and not the electrical excitation so crucial to realize integrated devices. It turns out that electrically excited SPASERs are a rather difficult problem to solve due to the Purcell effect: The spontaneous emission rate, characterized by broadband and incoherent plasmon emission, increases as the resonator's cavity volume decreases. In order to counter the Purcell effect, more energy must be supplied to the gain medium to achieve stimulated plasmon emission (i.e., spasing). For resonator volumes as small as metal nanoparticles, the electrical current required for spasing is greater than the gain material can physically handle. Electrical spasing requires development of new gain materials, artificial materials with engineered metal-like properties, or novel device designs that somehow circumvent the Purcell effect.

Some workers in the plasmonics community argue that spontaneous emission, generally regarded as an unwanted artifact for SPASERs, might be useful as a plasmon source in itself. Surface plasmon-emitting devices (SPEDs) are sources of broadband and incoherent plasmons generated from spontaneous emission and are analogous to their optical cousins. While a number of researchers strive to develop the SPASER, it is likely that SPEDs would be of great value for certain applications where broadband yet incoherent plasmon output is beneficial. Such an application might work for a plasmonic interconnect scheme.

SPASERs and SPEDs represent ideal plasmon sources. They are truly nanoscale devices made of compatible materials and have comparable dimensions with the smallest microprocessor structure. We are likely to see significant SPASER advances in the next five years. The coupling efficiency of nanoparticle plasmons from SPASERs and SPEDs to SPP waveguides will improve considerably and manufacturing processes that allow reliable device fabrication will be developed. The most important development will be the demonstration of electrical SPASERs and will be foretold by developments in high-gain semiconductor materials. This is a necessity for nanoparticle SPASERs, yet we believe that

the SPED may offer a worthwhile alternative for interconnect schemes requiring a broadband and power-efficient plasmon source.

Waveguides

As SPPs propagate on the surface of metals, a natural choice of an SPP waveguide would consist of a thin (< 50 nm) and narrow (< 200 nm) metal strip supported on a dielectric material. SPP waveguides are functional elements required to build more advanced devices such as splitters, couplers, modulators, and routers necessary for interconnect applications. In general, SPP waveguides support two types of SPP excitation: weakly bound long-range SPP modes (LRSPPs) and strongly bound short-range SPP modes (SRSPPs) regardless of the waveguide geometry.

There is one overarching generality with SPP waveguides no matter what the geometry—with increased plasmon confinement comes increased loss due to the metal itself. When an application requires very high confinement for ultradense signal propagation (e.g., intrachip core-core

communication), one must deal with the higher losses imposed by a more-confined SRSPP mode. Conversely, when an application requires longer range propagation (e.g., intraboard chip-memory communication) without dense signaling or more crosstalk immunity, one can opt for the less-confined LRSPP mode.

The loss experienced by SPP modes can be reduced, potentially compensated for (zero-loss), and even amplified by using a gain medium in conjunction with a metal waveguide. Partial loss compensation has been demonstrated by a number of authors on a variety of SPP structures using optical excitation [6, 7] with external pump lasers (see figure 3). For total loss compensation, the gain supplied to the system must equal the plasmonic losses, which in turn depends on the device geometry and the SPP modes. Researchers estimate 1,000–100,000 cm⁻¹ of gain is required for total loss compensation for SPP waveguides. In comparison, the highest gain achievable in semiconductor material is approximately 3,000 cm⁻¹, barely enough to provide full loss compensation for even LRSPPs.

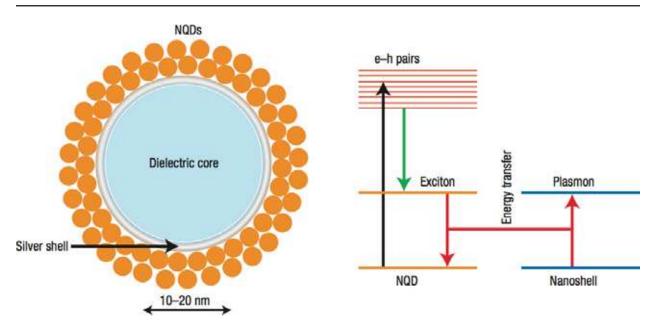


FIGURE 2. The most widely studied SPASER devices are comprised of metal nanoparticles that are coated with a gain material. This SPASER consists of a silver nanoshell particle surrounding a dielectric core and coated with nanocrystal quantum dot (NQD) gain medium (left). The spasing mechanism shows energy transfer between the gain medium and plasmon (right). Reprinted by permission from Macmillan Publishers Ltd: *Nature Photonics*, available at http://www.nature.com/nphoton/index.html, Stockman MI, "Spasers explained," doi: 10.1038/nphoton.2008.85, fig. 1 (a, b), 2008 [5].

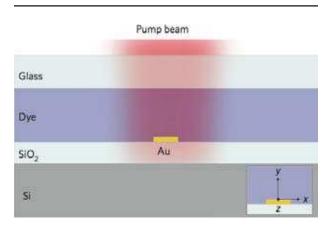


FIGURE 3. This cross section of an SPP waveguide device illustrates fractional loss compensation using optical excitation. Light from the pump beam (external to the device) excites dye molecules sandwiched between the silicon dioxide (SiO₂) fused quartz and glass layers—all supported on a silicon (Si) substrate. Plasmons propagating in the gold (Au) stripe waveguide are partially amplified (i.e., experience reduced losses) because of the excited dye molecules. As a result, the plasmon can propagate further thanks to the loss compensation. Reprinted by permission from Macmillan Publishers Ltd: *Nature Photonics*, available at http://www.nature.com/nphoton/index.html, De Leon I, Berini P, "Amplification of long-range surface plasmons by a dipolar gain medium," doi: 10.1038/nphoton.2010.37, fig. 1a, 2010 [7].

Given the integration of existing gain materials with SPP waveguides, we expect to see the first reports of loss compensated in LRSPP-mode waveguides using optical excitation within two years. This will require minimization of existing LRSPP-mode losses and a device design to maximize the plasmon field overlap with the gain medium. We anticipate this demonstration will spur development of new gain materials specifically for plasmonics that provide yet more gain, albeit in a narrow spectral range.

During the same period, we will see demonstrations of electrical excitation by current injection into the gain medium. This will be much more difficult in comparison to the optical excitation method. To prevent the available gain from being distributed over unwanted SPP modes, the waveguide has to be made small enough to support only the desired LRSPP or SRSPP mode(s), reducing the device volume, thus bringing the Purcell effect into play. Within five years, we anticipate electrical excitation of SPP waveguides that achieve total loss

compensation for both LRSPP and SRSPP modes. We also anticipate the development of artificial metal-like materials that exhibit low loss over a very narrow wavelength range. These developments will in turn enable all other elements critical to a plasmonic interconnect scheme and will herald maturation of plasmonic technology.

Detectors

The third and final major component in any future plasmonic interconnect scheme is the plasmon detector, namely a device that signals the arrival of SPPs by the output of a macroscopic voltage or current pulse. Two promising detection schemes exist for plasmon detection: the Schottky barrier detector (SBD) [8] and the superconducting nanowire single-plasmon detector (SNSPID) [9, 10]. Both detectors operate on the same principle by using the heat generated by decaying SPPs.

At the heart of an SBD is a semiconductor-metal junction, called a Schottky junction, which has an energy barrier height determined by the choice of semiconductor and metal (see figure 4). For example, gold on *n*-doped silicon has a Schottky barrier height of 0.83 electron volts. When a plasmon with energy greater than the Schottky barrier height decays, it leads to "hot carriers" being generated. These hot carriers overcome the Schottky barrier, generating an electrical current, which is detected by electronics and results in a plasmon detection event.

The sensitivity of SBDs depend on how small the Schottky junction can be made; large-area junctions suffer from high dark currents (i.e., false detection events) and are therefore less sensitive. Sensitivity can be increased by reducing the detector area, which in turn requires more plasmon decay in this smaller area. Therefore, sensitive SBDs can be realized using waveguides specifically designed to be extremely lossy (i.e., using the SRSPP mode). Other properties of SBDs, namely detection bandwidth and responsivity, can be tuned by using different metal-semiconductor combinations to alter the Schottky barrier height.

Current SBDs are capable of room-temperature operation and detection of plasmon power down to

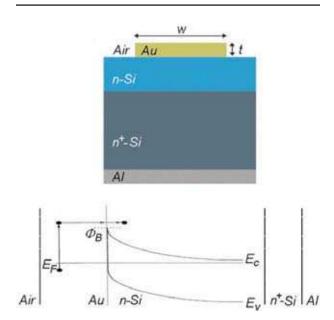


FIGURE 4. This cross section of a Schottky barrier plasmon detector (top) shows the gold (Au) waveguide and Au n-silicon (n-Si) Schottky barrier on an aluminum (Al) substrate. The junction energy level diagram (bottom) shows the Schottky barrier height (Φ_g). E_p , E_c , and E_v refer to the Fermi, conduction band, and valance band energies respectively, which are all dependent on the materials used. Reprinted with permission from *Applied Physics Letters*, Akbari A, Berini P, "Schottky contact surface-plasmon detector integrated with an asymmetric metal stripe waveguide," fig. 1, doi: 10.1063/1.3171937. Copyright 2009, AIP Publishing LLC [11].

-46 decibels per milliwatt (dBm) [12]. We expect device improvements to further reduce the dark current and increase sensitivity, with −60 dBm at a wavelength of 1.55 micrometers achievable within the next two years. For ultrasensitive and very lowpower plasmon detection, even down to the few- or single-plasmon level, SBDs have a long development path in front of them. SBDs are intrinsically fast devices, capable of detecting gigahertz rates thanks to their heritage as sub-bandgap photodetectors, and do not exhibit a dead-time effect. Over the next five years, we expect SBDs to become more sensitive and responsive; in fact, we expect to see demonstrations of devices as sensitive as Geigermode SBDs. We anticipate SBDs to become and remain the dominant technology in plasmon detection in the future.

SBDs are unlikely, in the near future at least, to detect down to the few- and single-plasmon level. Such a capability would be extremely useful in

applications where excessive loss is present, where loss-compensation schemes are unavailable, and also in emerging fields such as quantum plasmonics. For ultralow- to single-plasmon detection, we turn to the SNSPlD, itself also a derivative device from the photon-detection regime. SNSPlDs consist of a niobium-nitride nanowire structure grown in contact with or in close proximity to a plasmon waveguide. The entire device is cooled down to less than 10 kelvins (K; -263 °C), below the niobiumnitride superconducting critical temperature (T), using a liquid helium refrigerator. In an SNSPlD, the decaying plasmon locally heats the niobiumnitride nanowire, which results in a hotspot—a localized nonsuperconducting region with finite electrical resistance—and leads to a macroscopic current pulse.

SNSPIDs are extremely sensitive devices and, like their photon-detecting cousins, can detect single plasmons with efficiencies greater than 50% in the telecom wavelength band. The detector jitter, or timing uncertainty, is often very low at around 100 picoseconds, and SNSPIDs can operate at relatively high count rates exceeding hundreds of megahertz.

However, while all these detector specifications are impressive for single-plasmon counting applications, for high-bandwidth operation within a plasmonic interconnect scheme, one specific advance must be made for SNSPIDs to be a viable detector technology. The sub-10 K cooling is the most obvious drawback for SNSPID detectors, and the only practical way for SNSPlDs to be used in interconnect technology is for new high-T_c superconductors to be developed. This is not an easy problem to solve, and while we anticipate current research on high-T superconductivity to keep bearing fruit, we do not expect a disruptive high-T superconductor breakthrough within the next five years. This unfortunately leaves SNSPlDs as a research tool primarily for single-plasmon applications and possibly interconnect schemes where the detectors can be located well away from the microprocessor.

Summary

Plasmonics offers the benefits of high-bandwidth signaling with physical confinement down to the true nanoscale due to the metals on which plasmons are supported. Plasmonic interconnects is a major contender as a future technology to alleviate the current communications bottleneck in computer architectures. We have introduced three major plasmonic technologies necessary to realize this vision: 1) plasmon sources such as nanolasers, SPASERs, and SPEDs; 2) low- and zero-loss plasmon waveguides, which in turn will be necessary for splitters, modulators, and routers; and 3) efficient plasmon detectors. However, the metal which permits nanoscale confinement of an optical field is also a great disadvantage due to losses incurred. Therefore, we anticipate some major breakthroughs within the next five years on development of gain materials and artificial metal-like materials specifically for plasmonics applications. This will result in demonstrations of low- and zero-loss waveguides and electrical injection spasing. We also expect developments in plasmonic detectors leading lownoise and high-sensitivity plasmon detection. These advances will likely propel plasmonics forward at

a rapid pace, enabling practical plasmonic devices and bringing the plasmonic interconnect vision closer to reality.

About the author

This work was performed at **Oak Ridge National Laboratory (ORNL)**, operated by UT-Battelle, LLC for the US Department of Energy under contract number DE-AC05-00OR22725. Scientists and engineers at ORNL conduct basic and applied research and development to create scientific knowledge and technological solutions that strengthen the nation's leadership in key areas of science; increase the availability of clean, abundant energy; restore and protect the environment; and contribute to national security. Specific program thrusts include ultrascale computing, cyber/energy infrastructure protection, quantum information science, homeland protection, and difficult problems that face the intelligence community.

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